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SOLAR NEON ABUNDANCES FROM GAMMA-RAY SPECTROSCOPY AND ^{3}He-RICH PARTICLE EVENTS

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ABSTRACT

We compare ambient solar atmospheric abundances derived from gamma-ray spectroscopy with observations of solar energetic particles. We find agreement between the gamma-ray–derived Ne/O ratio and the corresponding mean ratio for ^{3}He-rich flares. Both of these values are significantly higher than inferred coronal Ne/O ratios. We suggest that the mean Ne/O ratio in ^{3}He-rich flares reflects the composition of the flare plasma rather than the acceleration process.

Subject headings: gamma rays: general — Sun: abundances — Sun: flares — Sun: solar wind

I. INTRODUCTION

Information on the Ne abundance in the solar atmosphere has been obtained from spectroscopic observations of the corona (see Meyer 1985 and references therein), solar wind observations (Bochsler, Geiss, and Kunz 1986), and observations of solar flare accelerated particles in interplanetary space (Mason *et al.* 1980, 1986; Breneman and Stone 1985; McGuire, von Rosenvinge, and McDonald 1986). All of these techniques are subject to uncertainties. The coronal spectroscopic observations are uncertain because of poorly known ionization conditions, and the abundances deduced from particle and solar wind observations are uncertain because of fractionation effects caused by acceleration. The particle observations, in particular, show large variabilities whose origin is not well understood. Furthermore, none of the above techniques measures the photospheric Ne abundance, which has not yet been measured directly. It is thought (e.g., Meyer 1985; Vauclair and Meyer 1985) that particles are transported from the photosphere into the corona by a process that favors charged particles. Since in the photosphere atoms are ionized predominantly by collisions, this process would lead to suppressed coronal abundances relative to photospheric abundances for elements with high first ionization potential.

Gamma-ray spectroscopy has provided a new technique for solar abundance determinations (Murphy *et al.* 1985*a*, *b*; see also Ramaty and Murphy 1987). The gamma-ray method allows the determination of abundances of the ambient gas in the gamma-ray production region, which is thought to be contained in a flare loop or loops below the chromosphere-corona transition region. Abundances for six elements, C, O, Ne, Mg, Si, and Fe, were derived by this method for the 1981 April 27 flare. Normalizing the Ne abundance to that of O, we find that the Ne/O ratio obtained from the gamma-ray method, $(\mathrm{Ne/O})_{\mathrm{gr}} = 0.47 \pm 0.09$, is significantly higher than the corresponding ratios in the corona, $(\mathrm{Ne/O})_{\mathrm{cor}} = 0.14 \pm 0.12$ (Meyer 1985) and in the solar wind, $(\mathrm{Ne/O})_{\mathrm{sw}} = 0.17 \pm 0.02$ (Bochsler, Geiss, and Kunz 1986). We note that both the Ne and O abundances are derived from strong lines, at 1.634 and 6.129 MeV, respectively. Since the solar wind abundances probably reflect coronal abundances, this result indicates that there could be significant differences between the chromospheric Ne/O ratio at the base of a flare loop and the corresponding ratio in the corona.

We can also compare $(\mathrm{Ne/O})_{\mathrm{gr}}$ with Ne/O ratios in solar energetic particles, $(\mathrm{Ne/O})_{\mathrm{sep}}$. But we must keep in mind the large variability of $(\mathrm{Ne/O})_{\mathrm{sep}}$. If we classify the particle events according to whether they are poor or rich in ^{3}He, then for the non–^{3}He-rich events, which tend to be large particle events, $(\mathrm{Ne/O})_{\mathrm{gr}}$ is still significantly larger than the mean $(\mathrm{Ne/O})_{\mathrm{sep}} = 0.15$ (Mason *et al.* 1980; Breneman and Stone 1985; McGuire, von Rosenvinge, and McDonald 1986). But, as we show in the present work, for ^{3}He-rich events, $(\mathrm{Ne/O})_{\mathrm{gr}}$ is quite consistent with the mean $(\mathrm{Ne/O})_{\mathrm{sep}} \approx 0.42$. Large particle events probably result from shock-accelerated coronal material, while ^{3}He-rich events, being closely associated with the impulsive phase of solar flares, probably result from acceleration of hot flare plasma (e.g., Lin 1987). The mechanism which enriches ^{3}He is not well understood, but selective heating of the ^{3}He nuclei due to wave-particle interactions (Fisk 1978; Kocharov and Kocharov 1978; Varvoglis and Papadopoulos 1983; see also Weatherall 1984) could be responsible for their preferential acceleration. Such selective heating can also lead to the preferential acceleration of partially stripped ions and account for the observed (e.g., Mason *et al.* 1986) enrichment of heavy-element abundances in ^{3}He-rich flares. *A priori*, we might expect that the enhancement of $(\mathrm{Ne/O})_{\mathrm{sep}}$ in ^{3}He-rich events relative to the large events is caused by selective heating. But since the ionic states of Ne and O in the flare-heated material are not expected to be very different, it is unlikely that selective heating and preferential acceleration can introduce large variation in the Ne/O ratio.

In this *Letter* we make the first comparison of abundances derived from gamma-ray spectroscopy with those of the energetic particles from ^{3}He-rich flares. By comparing the abundances deduced from the gamma-ray method with those observed in the emitted particles, it becomes possible to distinguish the enhancements that depend upon selective acceleration from those that exist independently in the ambient gas. We find that, in addition to possible selective acceleration effects, the Ne/O ratio in the flare plasma is significantly enhanced relative to the corona.

II. RESULTS OF THE OBSERVATIONS

We first consider the particle data. Rather than considering individual flares, we study daily-averaged particle intensities. This technique samples the total particle flux at 1 AU. But since nearly all of these particles are of solar and inner heliospheric origin, rather than from the outer heliosphere or the Galaxy, our derived abundances clearly pertain to solar material. As opposed to studies which distinguish individual flares, the advantage of the present technique, first employed by Mason *et al.* (1980), is that it considers particles from all types of solar acceleration, including acceleration by coronal and interplanetary shocks.

We show in Figure 1 distributions of abundance ratios of C, Ne, Mg, Si, and Fe relative to O obtained from observations with detectors aboard the *ISEE 3* spacecraft (von Rosenvinge *et al.* 1978) during the period 1978 August 15 to 1987 February 7 (see Reames 1988*b*). Each distribution was constructed from data in the 1.9 to 2.8 MeV amu^{-1} range obtained on days in which the average particle intensities for each species exceeded 10^{-4} particles cm^{-2} s^{-1} sr^{-1} (MeV amu^{-1})$^{-1}$. The ordinates in Figure 1 give the number of days in which the abundance ratio is in the indicated range. As can be seen, the solar energetic particle abundance ratios, especially Fe/O, exhibit very large variations.

Along with the above nuclei, ^{3}He and ^{4}He were also measured, and daily-averaged ^{3}He/^{4}He ratios in the 1.3 to 1.6 MeV amu^{-1} range were constructed. The blackened distributions represent a subset of the data obtained with the constraint that the daily-averaged ^{3}He/^{4}He ratio exceeds 0.1. As opposed to the unconstrained abundances, which pertain to all types of solar acceleration, the abundances associated with the high ^{3}He/^{4}He ratios (>0.1) pertain to impulsive solar flares, because episodes of particle emission with enhanced ^{3}He/^{4}He ratios have been clearly associated with impulsive solar flare phenomena (Reames *et al.* 1988).

The abundances derived (Murphy *et al.* 1985*a*, *b*; Ramaty and Murphy 1987) by the gamma-ray method for the 1981 April 27 flare are shown by the filled circles in Figure 1. This method is based on the comparison of observed nuclear deexcitation line spectra (Forrest 1983) with calculated spectra (Ramaty, Kozlovsky, and Lingenfelter 1979; Murphy 1985), where the latter are obtained from gamma-ray production models. These models incorporate the relevant nuclear excitation cross sections, the most important of which have been directly measured (e.g., Dyer *et al.* 1981; Lang *et al.* 1987). The derived abundances depend primarily on the intensities of narrow nuclear lines, resulting from interactions of accelerated protons and α particles with C and heavier nuclei in the ambient gas. The resultant abundances, therefore, are those of the ambient medium in the gamma-ray production region. A variety of arguments (Murphy and Ramaty 1984), as well as recent studies of ion transport in solar flares (Ramaty *et al.* 1988), indicate that the bulk of the gamma rays are produced in closed magnetic loops, at atmospheric heights extending approximately from the upper photosphere to the transition region. It should be emphasized that the abundances derived from gamma-ray spectroscopy are independent of the temperature and ionization state of the emitting material. However, the technique is still quite limited because data are currently available from only one flare. Therefore, it is not yet possible to examine whether the abundances derived by the gamma-ray method vary from flare to flare.

There is as yet no flare for which abundances were deduced simultaneously from gamma-ray and energetic particle observations. While particle observations are available following the 1981 April 27 flare, no discrete particle increase could be attributed to this flare and therefore energetic particle abundances cannot be derived. The lack of a discrete particle increase could be caused by poor magnetic connection of the 1981 April 27 flare (W90°) to *ISEE 3* and by the presence of a large flux of particles from earlier events.

III. DISCUSSION

Considering the data in Figure 1, we first point out that an enhanced ^{3}He/^{4}He ratio tends to define a separate class of solar acceleration events characterized by enhanced abundances of Ne and heavier elements relative to O. Indeed, a variety of observations suggest the existence of two distinct populations of accelerated particles, belonging to two classes of acceleration phenomena. Particles of the first class have much larger electron-to-proton (Cane, McGuire, and von Rosenvinge 1986) and ^{3}He/^{4}He ratios (Reames and Stone 1986), and are much more abundant in heavy elements (Mason *et al.* 1986; Reames 1988*b*) than those of the second class. First class particle events are well correlated with impulsive solar flare phenomena, such as type III radio emission, impulsive X-ray emission and nonrelativistic electron emission (Cane, McGuire, and von Rosenvinge 1986; Reames and Stone 1986; Lin 1987). Second class events are correlated with coronal mass ejections and types II and IV radio emissions (Kahler *et al.* 1984). It has been suggested that the particles in first class events are accelerated from hot flare plasma, while those of second class events are accelerated from ambient coronal gas (Lin 1987). This suggestion was based on the higher ionization state of Fe found in first class events relative to that in second class events (Klecker *et al.* 1984; Luhn *et al.* 1985). Further support for this suggestion is provided by the correlation of the Mg/He, Si/He, and Fe/He ratios in first class events with the temperature of the hot flare plasma, as measured by soft X-ray emission (Reames 1988*a*). Gamma-ray production in solar flares is mostly due to accelerated particles belonging to the first class (Chupp 1984).

In the comparison of the abundances derived from gamma-ray observations with those derived from energetic particle observations, we first consider the Ne/O ratios shown in Figure 1. We see that $(\mathrm{Ne/O})_{gr}$ is more consistent with the enhanced $(\mathrm{Ne/O})_{sep}$ associated with ^{3}He-rich events than with those events that are not rich in ^{3}He, with $(\mathrm{Ne/O})_{gr}$ agreeing quite well with the $(\mathrm{Ne/O})_{sep}$ corresponding to the peak of the distribution for ^{3}He-rich events. $(\mathrm{Ne/O})_{gr}$ clearly pertains to the ambient gas, and the ^{3}He-rich particle events originate from acceleration of flare plasma. Therefore, it is entirely plausible that the enhancement of $(\mathrm{Ne/O})_{sep}$ in ^{3}He-rich events is, at least partially, due to a significant enhancement of the Ne/O ratio in the flare plasma relative to the corona. Considering next the distributions for Mg, Si, and Fe, we see that the $(\mathrm{Mg/O})_{gr}$, $(\mathrm{Si/O})_{gr}$, and $(\mathrm{Fe/O})_{gr}$ ratios are all lower than the corresponding mean ratios for the ^{3}He-rich events and indeed are close to the medians shown for the events which are not rich in ^{3}He. This suggests that the enhancements in $(\mathrm{Mg/O})_{sep}$, $(\mathrm{Si/O})_{sep}$, and $(\mathrm{Fe/O})_{sep}$ in ^{3}He-rich events are predominantly due to preferential acceleration.

To test these suggestions, we have reexamined the correlation of heavy element abundance enhancements with flare temperatures derived from soft X-ray observations (Reames 1988*a*). This study involved abundance determinations in individual ^{3}He-rich events for which flare temperatures could be determined from soft X-ray observations (Reames *et al.* 1988). Using the same data, we show in Figure 2 the variation of $(\mathrm{Ne/O})_{sep}$ and $(\mathrm{Fe/O})_{sep}$ ratio with temperature. We have fitted

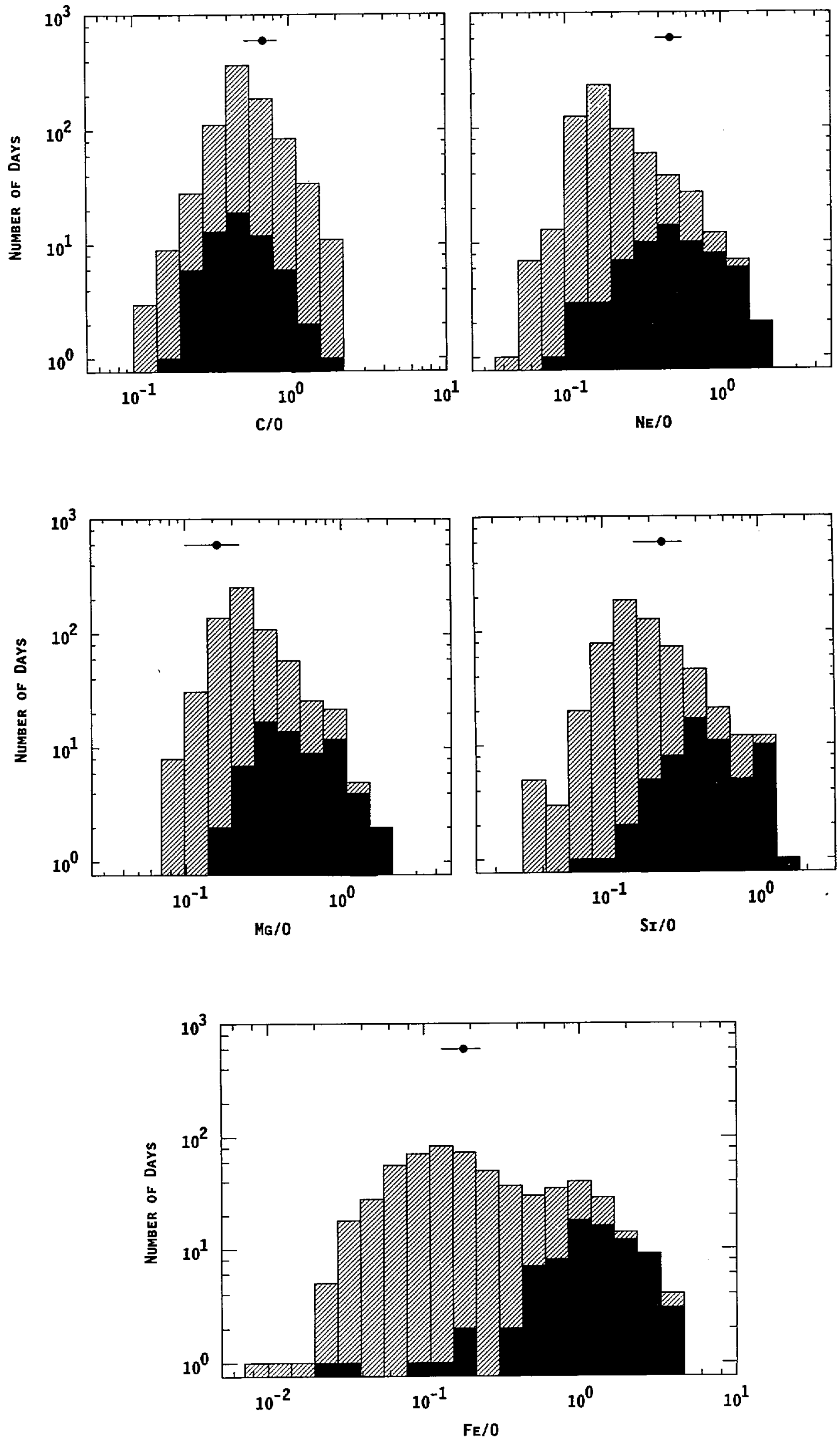

FIG. 1.—Abundance distributions. The histograms are based on daily-averaged energetic particle observations in interplanetary space. Days corresponding to $^3He/^4He$ ratios exceeding 0.1 are shown by the blackened distributions. The filled circles with horizontal error bars shown near the top of each panel were derived from gamma-ray observations.

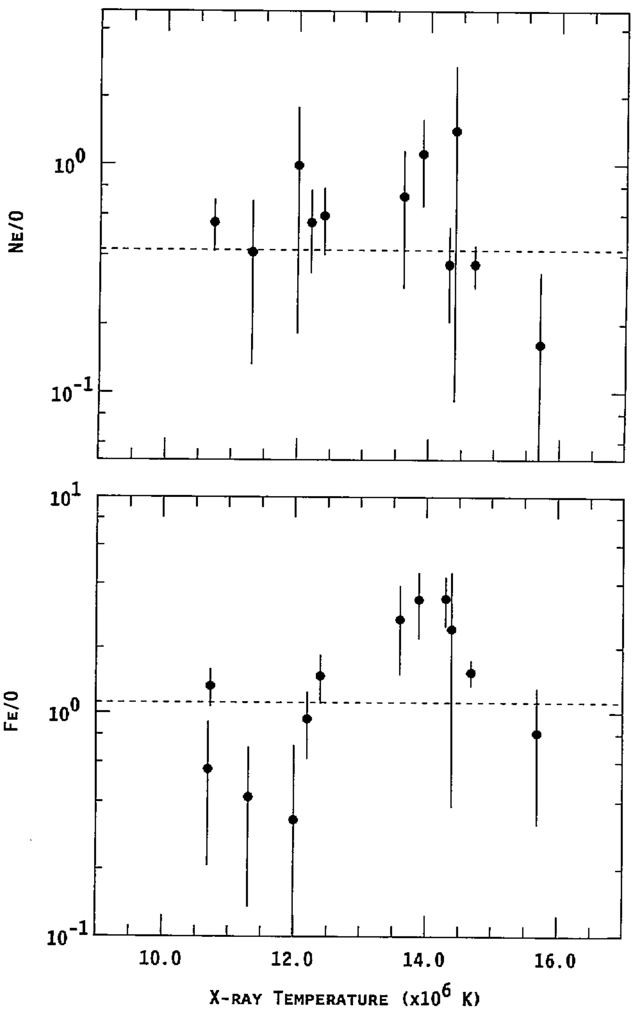

FIG. 2.—The dependence on flare temperature of the Ne/O and Fe/O ratios for individual ^{3}He-rich flares. The temperatures were determined from soft X-ray observations of the flares.

each abundance ratio to a constant, temperature-independent value shown by a dashed line. The resultant minimum reduced $\chi_\nu^2 = 0.87$ ($\nu = 10$) for Ne suggests that the $(\mathrm{Ne/O})_{\mathrm{sep}}$ ratios are not correlated with temperature and are thus consistent with a mean value, 0.42 ± 0.03, which is in good agreement with the gamma-ray derived value. For Fe, $\chi_\nu^2 = 2.92$ ($\nu = 11$), implying that $(\mathrm{Fe/O})_{\mathrm{sep}}$ does depend on the flare temperature and thus the Fe enhancement could arise from preferential acceleration.

The implication of our results is that the Ne/O ratio in the ambient gas in flares is significantly higher than in the average nonflaring solar corona. The gamma-ray derived ambient-gas abundances for C, O, Mg, Si, and Fe were compared previously with photospheric abundances by Murphy *et al.* (1985*a*, *b*). The results show that the abundances of Mg, Si, and Fe are consistent with photospheric abundances, and that the abundances of C and O are suppressed relative to those of the photosphere. These suppressions are consistent with the first ionization potentials of C and O, which are higher than those of Mg, Si, and Fe. While the photospheric Ne abundance has not yet been measured directly, it is possible that the Ne/O ratio in the photosphere is similar to the local galactic Ne/O ratio, which is in agreement with the coronal Ne/O ratio (Meyer 1985). If this is the case, then the gamma-ray derived abundance of Ne (relative to Mg, Si, or Fe) is consistent with its photospheric abundance and the enhanced Ne/O ratio results from the suppression of O (Murphy *et al.* 1985*a*, *b*). This result, however, is inconsistent with the first ionization potential of Ne, which is higher than that of O. Therefore, either the photospheric Ne/O ratio is higher than the local galactic Ne/O ratio, or the abundances of the ambient gas in flares do not correlate with first ionization potential.

III. CONCLUSIONS

We have presented solar energetic particle abundances and compared them with ambient solar flare abundances derived from gamma-ray spectroscopy. For the Ne abundance, in particular, we found agreement between the gamma-ray derived Ne/O ratio and the mean value of this ratio for ^{3}He-rich events. Both of these values are significantly higher than the mean Ne/O ratios in the solar wind, in the solar corona, and in non–^{3}He-rich energetic particle events. These latter values most likely pertain to the solar corona. Since both gamma-ray emission and the particles in ^{3}He-rich events are produced by impulsive solar flares, we concluded that the ambient flare plasma is either enriched in Ne or depleted in O. We also examined the temperature dependence of the Ne/O ratio in ^{3}He-rich flares. We found no correlation of this Ne/O ratio with temperature, in contrast with the corresponding Fe/O ratio which shows a strong temperature dependence. We presented this finding as additional evidence for our conclusion that the enhanced Ne/O ratio in ^{3}He-rich flares reflects the ambient flare plasma composition. Important limitations on our conclusion are imposed by the fact that there is as yet no example of a flare in which both gamma-ray and energetic particle abundances were simultaneously deduced, and by the availability of gamma-ray derived abundances from only one flare.

Abundance variations are observed at various nonsolar sites as well. For example, in planetary nebulae (Aller and Keyes 1987) the Ne/O ratio was found to vary from object to object in the range 0.1–0.6, with a mean value of 0.24 ± 0.01. In view of our solar results, we would like to suggest that these variations could also arise from processes similar to those that operate in the solar atmosphere, in addition to possible differences in the nucleosynthetic histories of the various nebulae.

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